Active Vibration Control of a Large Flexible Manipulator
By Inertial Force and Joint Torque

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Contents

Abstract

The efficiency and positional accuracy of a lightweight flexible manipulator are limited by its flexural vibrations, which last after a gross motion is completed. The vibration delays subsequent operations.

In the proposed work, the vibration is suppressed by inertial force of a small arm in addition to the joint actuators and passive damping treatment. The proposed approach is : 1) Dynamic modeling of a combined system, a large flexible manipulator and a small arm, 2) Determination of optimal sensor location and controller algorithm, and 3) Verification of the fitness of model and the performance of controller.

I. Introduction

Most industrial robots have limitations on efficient usage and wide application because of short arm lengths and **heavy** steel construction. An alternative approach to expand the capabilities is to design the robot with light weight flexible links which have safe strength.

A large, two degree of freedom flexible manipulator which has a small arm at one end has been constructed at the Flexible Automation Laboratory in Georgia Institute of Technology as shown in Fig. 1. The large flexible manipulator is for gross motions, and the small arm is for fine motions. The large manipulator consists of two ten foot long links made of aluminum tubing actuated hydraulically through a parallel link drive. The small arm is actuated by three brushless D.C. motors through harmonic drives at each joint.

Such a configuration has many advantages compared to conventional industrial robots, that is, larger workspace, faster motion time for large motion and higher payload to weight ratios. It would be useful for welding, riveting, assembly, and inspection of large vessels, structures and vehicles. The manipulator, however, has some technical problems that need to be solved. Such problems are due to the flexibility of the large manipulator, dynamic coupling between the large manipulator and the small arm, and the friction and elasticity of a drive at the joints of the small arm.

The amplitude of the flexural vibration of the manipulator increases with operating speed and payload. In order to apply a bracing strategy[5] for efficiency and positioning accuracy without collision between contacting parts, the vibration of the

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manipulator needs to be suppressed as quickly as possible. Before working on fine motion jobs, the actuators of the small arm have little to do, and can generate inertial forces to reduce vibrations. In this research, the inertial force of the small arm is to be used for suppressing the vibrations of the large manipulator together with the hydraulic actuators of that arm and a passive damping treatment.

A variety of studies have been done to control the flexural vibration of a manipulator and a structure in several engineering areas. Most of them considered the control of one dimensional vibration of a beam-like structure[2],[21],[22],[26],[28],[31], a plate[1],[25], one link manipulator[7],[10], [14],[17], and two serial link manipulator [4],[12],[29]. Only a few of them have considered two dimensional vibration[9],[30], and dynamic coupling between a beam and an actuator[24]. However the proposed manipulator has some additional problems. First of all, the parallel link mechanism gives more complicated nonlinear dynamic equations, and the manipulator shows three directional vibrations induced by the inertial force of the small arm. Moreover the dynamics of the small arm are inherently coupled to the dynamics of the large manipulator. Such coupling must be modeled. The coupling is due to the fact that the reference frame of the small arm is dependent on the dynamics of the large manipulator. Also, the joint friction and flexibility of the small arm are not negligible. These features give complicated coupled nonlinear dynamic equations. In order to design a controller, the coupled dynamic equations should be determined and verified.

Besides the complexity of the dynamics, the manipulator has an infinite number of modes. It is practically impossible to design a controller based on an infinite dimensional dynamic model. The actuators, the hydraulic cylinder and the small arm, have limited bandwidths. Also, the limitations on cost and space restricts number of sensors to be used. Hence a controller should be designed with limited number

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of sensors and a reduced order model which exhibits the best dynamic performance within these limitations. In this case, truncated higher modes can cause instability[2]. This phenomenon is called spillover. The spillover instability depends on the dynamics of a controlled system[16] and the location of sensors[17]. Since the proposed manipulator has highly coupled dynamic equations. A more sophisticated control algorithm is required to obtain stability. The spillover phenomenon will be studied by computer simulation, and examined by experiments. In relation to this problem, the effectiveness of the passive damping is to be studied. Also, the optimal location of sensors and the optimal posture of the small arm will be studied.

In positioning stages, the movement of the large manipulator is small compared to the gross motion. Then the dynamic equations can be linearized at a certain configuration. These linearized equations will be used for a controller design. The characteristics of the equations varies with the change in the payload and the configuration of the manipulator. Modeling errors are inevitable. In order to obtain a good performance, the controller designed should compensate the modeling errors and adapt the change of the dynamic characteristics. At the first stage of this research, a simple control algorithm will be used to examine the system performance. Later more sophisticated controller will be designed.

II. Related Previous Work

The dynamics of a flexible manipulator is viewed as coupled rigid and flexible motion. The flexible motion is governed by a partial differential equation. In order to obtain ordinary differential equations from the partial differential equation , modal analysis is commonly used.

The flexible manipulator can be modeled in terms of either constrained modes of vibration where the joint is held motionless, or the unconstrained modes of vibration where the entire body vibrates. Most researchers have used constrained modes in a dynamic modeling. In one link arm, the dynamic model using the constrained modes showed good agreement with the results of experiments[9],[14], [17]. A few researchers studied multi-link arms using the constrained modes [4],[27],[29]. In the case of multi-link arm, dynamic interactions between the links affect the boundary conditions at the joints. Hence the selection of mode shapes is a difficult problem. The accuracy of the constrained mode method has not been experimentally confirmed in modeling a multi-link arm.

A few researchers used unconstrained modes in a dynamic modeling. In this case, the dynamic model using unconstrained mode is more rigorous. However the determination of the eigenfunctions becomes more complicated as the number of links increases. Using the unconstrained mode, Cannon Jr. and Schmitz[7], and Fukuda and Arakawa[12] derived a dynamic model for a one link arm and for a two link arm respectively.

Another approach in modal analysis is to use the finite element method. Usoro et al[34] modeled a two link arm by the finite element method. Lee[19] is also mod-

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eling the manipulator having parallel link mechanism by the finite element method. The finite element method is useful for the complicated structure whose boundary conditions are difficult to identify.

Several researchers have investigated joint flexibility and friction. Joint flexibility can cause large amplitude vibration and inaccurate positioning. The flexibility due to a harmonic drive shows nonlinear behavior similar to that of a hardening spring [35]. Sweet and Good[32] derived a nonlinear model for a robot drive system, which had strong anti-resonance/resonance properties. However, most researchers assume the joint flexibility to be a linear spring[11],[20],[23]. They confirmed the assumption by experiments.

Friction is always present to some extent, and causes poor motion accuracy. To find an exact model is difficult, hence several models of friction have been discussed in the literature[8],[13]. Canudas, et al[8] modeled static and viscous friction as nonlinear functions of angular velocity. Kubo, et al[18] used ideal Coulomb friction model in controlling a robot arm.

To control flexural vibration, most researchers have used joint actuators. The joint actuator also controls rigid body motion. An alternative is to use additional actuators which control flexible motions. A few researchers have studied this. Zalucky, and Hardt[36] designed two parallel beams with a hydraulic actuator mounted at one end. This arrangement was used to compensate deflection and to improve dynamic response. A similar configuration was applied to tracking control[10]. Singh and Schy[30] studied control of the vibration by external forces acting at one end. All of them neglected dynamic coupling between the actuator and manipulator. However, the movement of the manipulator can affect actuator dynamics. Ozguner and Yurkovich [24] have studied the vibration control of a beam coupled dynamically with

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an actuator, but their work is still preliminary. Chiang[37] studied a fast wrist to achieve better end point control when a large link was vibrating. He decoupled the dynamic motion of the end point from the movement of the large link by locating the end point at the center of percussion of the wrist.

The flexural vibration has an infinite number of modes. But it is more difficult to design a controller based on an infinite dimensional model. Hence, all of the researchers have used a reduced order model for designing a controller[4],[29],[7]. In this case, control and observation spillover can occur. Balas[2] showed that the effect of spillover could destabilize a large flexible space structure system. He suggested a comb filter to eliminate the instability. However Trunckenbrodt[33] indicated that the control spillover was not necessarily bad, and the comb filter was not useful for preventing the observation spillover instability. Book, Dickerson et al[6] proposed a passive damper to overcome the spillover instability. They showed that an unstable system due to truncated higher modes could be stabilized by passive damper. Alberts et al[0] suggested a combined active/passive control scheme. They improved system's stability using a constrained viscoelastic layer method.

III. The Objective of the Research

Many researchers have studied the control of a flexible manipulator. However, most of them have used only joint actuators for the vibration control. The objective of this research is to develop a control scheme which suppresses the vibration of the large flexible manipulator in minimum time. This is approached by using the inertial force of a small arm as well as the joint actuators and passive damping. The issues surrounding the change of configuration of both the large and small arm will be addressed. When the large manipulator changes configuration, the modes of the manipulator change. When the small arm changes configuration, the ability to influence these modes will change. The result of the proposed research may contribute to the modeling and control of the flexible manipulator with high efficiency and positional accuracy. No previous study of this type is known.

IV. Proposed Approach

The small arm will be used as the actuator for suppressing the flexural vibration. Hence it is important to find the dynamic characteristics of the small arm. Its links are essentially rigid but its joints have flexibility and friction. Its friction and flexibility will be identified by experiment.

Although much work has been done on modeling the large flexible manipulator at Georgia Tech[15],[19], they have not included the dynamics of the small arm and the out of plane motions of the manipulator. The dynamics of the combined system will be obtained by applying Lagrange's equations to the energy terms which are to be derived with assumed mode shapes. The mode shapes will be found by using the finite element method.

The dynamic equations of motion could be linearized at a certain configuration. The linearized equations can be written as

$$
\begin{bmatrix} M_{rr} & M_{rf} \\ M_{fr} & M_{ff} \end{bmatrix} \begin{bmatrix} \ddot{q}_r \\ \ddot{q}_f \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & D \end{bmatrix} \begin{bmatrix} \dot{q}_r \\ \dot{q}_f \end{bmatrix} + \begin{bmatrix} 0 & 0 \\ 0 & K \end{bmatrix} \begin{bmatrix} q_r \\ q_f \end{bmatrix} = \begin{bmatrix} N_r \\ N_f \end{bmatrix} \tau \quad (1)
$$

where subscripts r and f denote rigid and flexible coordinates respectively, q is generalized coordinate vector, M is generalized mass matrix, D is damping matrix, K is elastic stiffness matrix, N is input matrix, and τ is generalized force vector related to joint torque. The dynamics of the combined system will be verified by experiments.

The equation (1) can be expressed in state variable form as

$$
\begin{bmatrix} \dot{X}_c \\ \dot{X}_t \end{bmatrix} = \begin{bmatrix} A_{cc} & A_{ct} \\ A_{tc} & A_{tt} \end{bmatrix} \begin{bmatrix} X_c \\ X_t \end{bmatrix} + \begin{bmatrix} B_c \\ B_t \end{bmatrix} U \quad (2)
$$

where subscript c and t denote controlled modes and truncated modes respectively. Theoretically, the system has an infinite number of modes, but considering passive and structural damping, one can assume that the sum of n and t modes accurately represents dynamic behavior. The control law of the reduced order system can be given by

$$U = -FX_c, \tag{3}$$

where $\mathbf{F}$ is the feedback gain matrix.

By using equations (2),(3) and a matrix $\mathbf{C}$ included in the output equations, the full order closed loop system can be written as

$$\left[\begin{array}{c} \dot{X}_c \\ \dot{X}_t \end{array} \right] = \left[\begin{array}{cc} A_{cc} - B_cFC_c & A_{ct} - B_cFC_t \\ A_{tc} - B_tFC_c & A_{tt} - B_tFC_t \end{array} \right] \left[\begin{array}{c} X_c \\ X_t \end{array} \right] \tag{4}$$

or simply

$$\dot{X} = \tilde{A}X \tag{5}$$

Even though the reduced order closed loop system, $A_c - B_cFC_c$, is stable, the full order system can be unstable. The matrices $\mathbf{A}$ and $\mathbf{B}$ are related the posture of the small arm and the configuration of the large manipulator. The matrix $\mathbf{C}$ is a function of sensor location. Hence an optimally selected gain, sensor location and posture give the minimum real part of the eigenvalues of $\tilde{A}$. These will be studied computationally.

At first stage of this research, the constant gain matrix $\mathbf{F}$ will be used in the experiment. The displacement and velocity of the vibration will be estimated from the measured signal of strain gages and acoustic gap sensors. A controller should process many input and output signals with high speed. In order to increase the processing

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rate of the controller, multiple processors will be used. Later more sophisticated control algorithms, such as decentralized adaptive control and robust sliding mode control algorithm, will be considered for implementation.
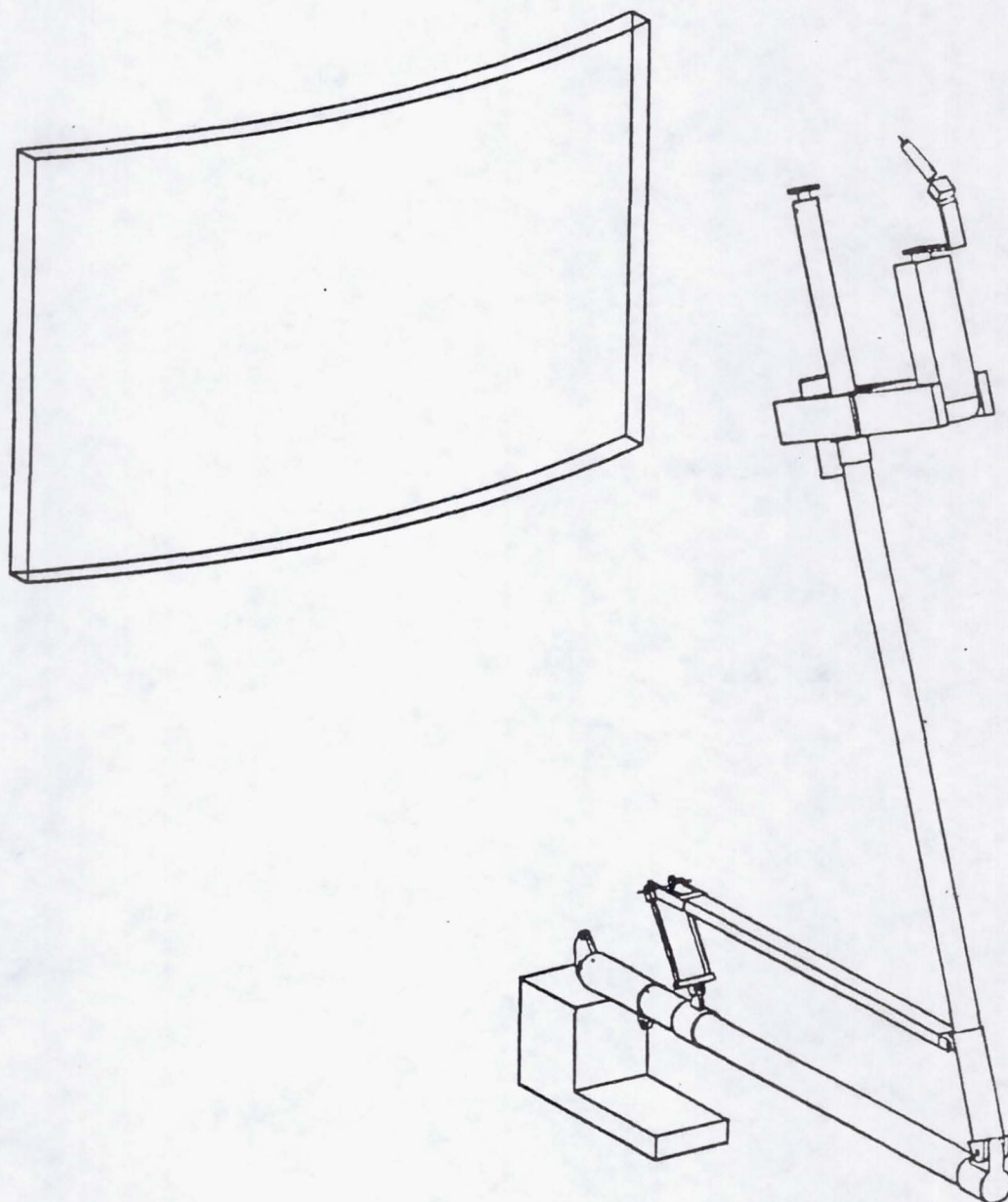
Figure 1: The Robotic Arm, Large and Flexible (RALF) carrying the Small Articulated Manipulator (SAM).

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